A Heat Transfer Model for a Stratified Corium-Metal Pool in the Lower Plenum of a Nuclear Reactor

M. S. Sohal
L. J. Siefken

Idaho National Engineering and Environmental Laboratory
Lockheed Martin Idaho Technologies Company
Idaho Falls, Idaho 83415

ABSTRACT

This preliminary design report describes a model for
heat transfer in a corium-metal stratified pool. It was
decided to make use the existing COUPLE model. Currently
available correlations for natural convection heat transfer
in a pool with and without internal heat generation were
obtained. The appropriate correlations will be incorporated

in the existing COUPLE model. Heat conduction and
solidification modeling will be done with existing
algorithms in the COUPLE. Assessment of the new model will
be done by simple energy conservation problems.

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EXECUTIVE SUMMARY

The objective of this design report is to develop a
model for heat transfer in stratified corium and metal pools
in a nuclear reactor lower head formed as a result of severe
accident. Natural convection heat transfer correlations in
pools with and without internal heat generation were
obtained from existing literature. It was decided to make
use of the existing COUPLE model and its algorithm to reduce
the coding cost. The appropriate correlations will be
incorporated in the COUPLE model. Heat conduction and
solidification modeling will be done with existing
algorithms in the COUPLE. The new model will be assessed by
energy conservation and other simple test problems, because
no exact experimental data are available.

1. INTRODUCTION

The SCDAP/RELAP51 computer code is designed to describe
the overall nuclear reactor coolant system thermal-hydraulic
response and core damage progression. The SCDAP code models
the core behavior and RELAP5 calculates the thermal
hydraulics during a severe accident. The code is being
developed at the Idaho National Engineering and
Environmental Laboratory (INEEL) under the sponsorship of U.
S. Nuclear Regulatory Commission (NRC). In a severe
accident scenario, the fuel and metal components such as
cladding and core plate may melt and slump into the lower
head of the reactor vessel. To avoid melting or structural
failure of the lower vessel, some reactors are designed to
have the lower head submerged in a pool of water in the
event of a severe accident. Thus, heat generated inside is
vessel is transferred to the water outside the vessel. To
calculate the temperature of the vessel wall, the heat
transfer from the molten material pool to the vessel walls
has to be calculated. This report discusses the heat
transfer model for heat transfer in the lower head after a
severe accident when the fuel, fuel-cladding material, and

metal components have slumped and settled in the lower head.

1.1 Objective

The multi-component and multi-phase mixture consisting of fuel, cladding, other metal and water in the lower head may form a homogeneous mixture or may stratify in two distinct layers. If the mixture stratifies, the upper layer may consist of lighter component of molten metal and the lower heavier layer may consist of corium (mixture of ZrO_2 and UO_2). The corium mixture is also the source of volumetric heat generation. Under certain thermal conditions, a crust of solid material may also form along the vessel wall and on the top of the layer containing corium mixture. The objective of this report is to develop a model to account for heat transfer from the mixture in the vessel to the vessel wall and to the environment lying above the upper layer under the given possible physical conditions. A model will be developed based on the available correlations for natural convection heat transfer in a hemispherical geometry.

2. BACKGROUND INFORMATION

During a TMI-2 like hypothetical nuclear reactor accident, the molten core relocates to the lower head. When the molten fuel interact with the coolant in the lower head, the fuel breaks up into small debris and eventually settle down on the bottom. Lighter molten metal may separate into a layer and settle on top of the corium volume as shown in Figure 1. The volumetric heat generation in the corium dissipates through the vessel wall by conduction and by radiates to the vessel volume above. The resulting temperature gradient in the liquid pool consisting of corium and molten metal will generate natural convection currents. Researchers have developed correlations for natural convection in hemispherical and cylindrical pools. Some of the basic phenomena and applicable correlations are reviewed in the following.

Figure 1. Schematic drawing of corium and metal pools in the lower head.

When a liquid pool is heated, the buoyant and viscous forces act in opposite directions on a fluid volume. The ratio of buoyant and viscous forces times the ratio of convective and conduction heat transfer is the characteristic dimensionless parameter and is called Rayleigh number. If the liquid volume is heated by external means, this number is called "external" Rayleigh number and is denoted by Ra. If the heating is caused by internal volumetric heat generation, this number is called "internal"

or "modified" Rayleigh number, Ra'. These two dimensionless numbers, Ra and Ra', are defined as   and , respectively,

where

g =   acceleration due to gravity (m/s2),

·   =   coefficient of thermal expansion (1/K),

?T   =   Temperature difference between bulk liquid and the boundary (K),

qv?   =   volumetric heat generation rate (W/m3),

L =   characteristic length (m),

a =   thermal diffusivity (m2/s),

?   =   kinematic viscosity (m2/s),

k =   thermal conductivity (W/m·K).

All the properties correspond to the fluid in question. Various researchers have used different values for the characteristic length. These values are: (1) the maximum radius of the liquid surface at the top of the pool, (2) maximum depth of the liquid pool, (3) an average of the maximum pool radius and the pool depth, and (4) radius of an equivalent hemispherical pool. In a correlation for Nusselt number, Nu = a (Ra' b), where b ~ 0.2, the characteristic length will cancel from the two sides and will not make any significant difference to the value of convective heat transfer coefficient, h. However, if b(for $7 \cdot 10^6$ = Ra' = $5 \cdot 10^{14}$) has a value far different than 0.2, and the liquid pool is not nearly hemispherical (either shallow or deep), then different definitions of characteristic lengths can effect the value of convective heat transfer coefficient. Therefore, except for a shallow molten metallic layer above corium pool, an average of liquid pool radius and pool height will be used.

The two Rayleigh numbers are related by a correlation

(1)

where   is called Damkîhler number.

2.1 Literature

After nuclear reactor core material slumps into the lower plenum, it goes through a significant amount of relocation and energy exchange. The entire molten pool of corium and metallic components may be treated as a homogeneous mixture as currently modeled in SCDAP. The

corium and metallic components may stratify forming a lower corium pool with metallic layer settling on the top. With time, each layer will get cooled and a solid crust of corium and metal may form around the respective liquid pools. The upper metal layer and lower corium pool also exchange energy with one another, which couples the energy balance in the two layers.

At present no well-accepted criterion or correlation exists that can determine whether there is one homogeneous liquid pool or two stratified pools. Therefore, the SCDAP user has to decide whether to model the liquid pool as one homogeneous pool or as two stratified layers.

Kelkar et al.[2] and Schmidt et al.[3] performed numerical analysis of natural convection in a hemispherical cavity. Kelkar et al.[2] also summarized several correlations for natural convection in enclosures. Similarly, Wang and Walton[4] also examined applicability of several correlations for natural convection in enclosures and developed the relationship between external and internal Rayleigh numbers. Theofanous et al.[5] have also examined the natural convection phenomenon in a hemispherical part of the reactor vessel. They examined both oxidic and metallic pools, and respective applicable natural convection correlations. The correlations given below for various physical conditions are based on the discussion given in these publications.

2.1.1   Natural Convection in a Pool with Internal Heat Generation

One of the useful correlations for natural convection was developed by Steinberner and Reineke[6]. They performed experiments with rectangular geometry with both upper and lower walls being cooled. Numerical modeling was used to develop Nusselt number, Nu, correlations for natural convection heat transfer in the upward and downward directions as shown in Figure 2. These correlations are given below. Subscripts u and d represent upward and downward heat transfer directions, respectively.

$$Nu_u = 0.345 \, Ra'^{\, 0.233} \quad (for \; 10^{10} = Ra' = 3.7 \cdot 10^{13}) \tag{2}$$

$$Nu_d = 1.389 \, Ra'^{\, 0.095} \quad (for \; 10^{10} = Ra' = 3.7 \cdot 10^{13}) \tag{3}$$

KymÑlÑinen et al.[7] performed experiments, in a facility called COPO (or mini ACOPO), on the heat flux distributions at the boundaries of a volumetrically heated pool with high Rayleigh numbers to simulate molten corium pool in a reactor vessel. The experimental facility consisted of a two-dimensional slice (of a hemispherical cavity) filled with H_2O-$ZnSO_4$. Their results showed that the upward heat flux

to the top boundary is somewhat conservatively represented by the relationship given by

Steinberner and Reineke[6] in Equation (3). Their data showed the applicability of Equation (3) for a Ra up to $6 \cdot 10^{14}$. For the vertical side walls, another correlation by Steinberner and Reineke[6] (Figure 2) fits the horizontal heat flow data satisfactorily. This is given in Equation (4);

$$Nu_h = 0.85 \, Ra^{0.19} \qquad \text{(for } 5 \cdot 10^{12} = Ra' = 10^{14}). \qquad (4)$$

This relation is applicable only in the turbulent flow regime, which is usually the case for corium pool. For a laminar flow regime, the only change from Equation (4) is that the numerical coefficient on the right hand side of Equation (4) changes to 0.6 as shown in Equation (5);

$$Nu_h = 0.6 \, Ra^{0.19} \qquad \text{(for } 10^7 = Ra' = 10^{10}). \qquad (5)$$

Figure 2. Nu versus Ra' correlations based on data of Steinberner and Reineke[6].

Figure 3. Upward heat transfer data correlation by Theofanous et al.[8]

Theofanous et al.[8] performed further experiments in a hemispherical facility called ACOPO, to measure heat transfer data. The upward heat transfer was compared with Steinberner and Reineke[6] correlation (Equation 2). It was determined that as Ra' reaches a high value in the range 10^{15}-10^{16}, Equation (2) deviates more and more from the ACOPO data. Therefore, Theofanous et al.[8] correlated the ACOPO data by the correlation given in Equation (6), which is compared with the data in Figure (3);

$$Nu_u = 0.9 \, Ra'^{0.2} \qquad \text{(for } 10^{14} = Ra' = 10^{17}). \qquad (6)$$

For downward heat transfer, Theofanous et al.[8] correlated their ACOPO data by the following correlation, as shown in Figure 4;

$$Nu_d = 0.048 \, Ra'^{0.27} \qquad \text{(for } 10^{14} = Ra' = 2 \cdot 10^{16}). \qquad (7)$$

Earlier, Theofanous et al.[5] correlated mini-ACOPO data for downward heat transfer by the following correlations, as

shown in Figure 5;

$$Nud \ = \ 0.048 \ Ra' \ 0.27 \qquad (\text{for } 1012 = Ra' = 3 \ ^{\cdot} \ 1013), \qquad (8)$$

$$Nud \ = \ 0.0038 \ Ra' \ 0.35 \quad (\text{for } 3 \ ^{\cdot} \ 1013 = Ra' = 7 \ ^{\cdot} \ 1014). \qquad (9)$$

Equations (7) and (8) are identical correlations. Equation (7) can predict the ACOPO and mini-ACOPO data quite reasonably except in the Rayleigh number range of $3 \ ^{\cdot} \ 1013 = Ra' = 7 \ ^{\cdot} \ 1014$. Mayinger et al.9 developed the following correlation for downward heat transfer based on their numerical solution of the natural convection problem;

$$Nud \ = \ 0.55 \ Ra' \ 0.2 \qquad (\text{for } 7 \ ^{\cdot} \ 106 = Ra' = 5 \ ^{\cdot} \ 1014). \qquad (10)$$

Figures 6 and 7 compare the predictions by Equation (10) with the data from mini-ACOPO, ACOPO, Asfia and Dhir10, and numerical results of Kelkar et al.11 It can be seen from Figure (6) that Equation (10) has a significantly different slope than the data. In fact, Equation (9) appears to be a better fit to the data. In Figure (7), although the data are bounded by Equation (10) and Equation (8). Therefore, there appears to be no advantage of using Equation (10) over Equations (8) or (9). Based on these observations, Equation (10) will not be used for our analysis.

Figure 4. Downward heat transfer data correlation by Theofanous et al.8

Figure 5. Correlation (Equations 8 and 9) of mini-ACOPO data for downward heat transfer by Theofanous et al.5

Figure 6. Comparison of Equations (10) predictions with experimental data and numerical results for downward heat transfer5.

Figure 7. Comparisons of Equation (10) predictions with ACOPO data for downward heat transfer5.

2.1.2   Natural Convection in a Pool with no Internal Heat Generation

If stratification takes place in a molten pool of the

nuclear reactor, molten metal collects above the corium pool. Molten metal has no internal heat generation, but is heated by the corium pool from below. Therefore, in this case, the "external" Rayleigh number, Ra, will be applicable for natural convection heat transfer correlations.

One of the earliest correlations for natural convection between two horizontal plates is by Globe and Dropkin[12]. However, recently Park et al.[13] performed experiments to simulate a molten metal pool in a nuclear reactor. It was determined that although Globe and Dropkin's correlation, given in Equation (11) does reasonable job of fitting their data, their new correlation, given in Equation (12), is somewhat better. This fact can be seen in Figure (8). The Globe and Dropkin and the Park et al. Correlations are;

$$Nu_u = 0.051 \ Ra^{1/3}, \tag{11}$$

$$Nu_u = 0.0923 \ Ra^{0.302} \qquad (\text{for } 2 \cdot 10^4 = Ra = 2 \cdot 10^7). \tag{12}$$

Theofanous et al.[5] has also recommended using a correlation like that in Equation (11). Based on the work by O'Toole and Silveston[14], for a Prandtl number of 0.13, Theofanous et al.[5] arrived at the following correlation;

$$Nu_u = 0.088 \ Ra^{0.305}. \tag{13}$$

Correlation in Equation (13) is nearly the same as given by Park et al.[13] in Equation (12). It should also be noted that Park et al.[13] have defined the "external" Rayleigh number with characteristic length being equal to the height of the liquid metal pool.

For the molten metal pool, no experimentally verified correlation exists for the heat transfer (Nusselt number) in the horizontal direction to the vertical vessel walls. Therefore, the Nusselt number can be estimated by using either Equation (5) with a different definition of Rayleigh number (Ra) or Equation (12). There is no experimental data to test the validity of either correlation. Equations (5) and (12) give the same results near $Ra = 10^7$. Because slopes of the two correlations are different (0.19 versus 0.302), Equation (5) will give higher values of Nu_h for $Ra < 10^7$. Whereas for $Ra > 10^7$, Equation (12) will give higher value of Nu_h. Therefore, at present it is suggested that an average of Equations (5) and (12) be used, which is;

$$Nu_h = 0.5 \ (0.6 \ Ra^{0.19} + 0.0923 \ Ra^{0.302}). \tag{14}$$

Figure 8. Natural convection upward heat transfer data and

3. SELECTED NUSSELT NO. VERSUS RAYLEIGH NO. CORRELATIONS

The previous section presented a summary of Nusselt number versus Rayleigh number correlations based on the experimental and numerical investigations. However, all the experiments are simulations using water or Freon. None of the experiments had two stratified pools, one representing corium and other representing molten metal. Therefore, the correlations given in Table 1 represent best available information on the corium-metal pool natural convection heat transfer. Table 1 lists various correlations for natural convection Nusselt number in a hemispherical cavity with and without internal heat generation.

Table 1. Selected Nu vs. Ra Correlations

	Heat Transfer Direction	Nu versus Ra Correlation	Rayleigh No. Range
With Internal Heat Generation (Corium Pool)	Up	$Nu_u = 0.345\ Ra'^{0.233}$	$10^{10} \leq Ra' \leq 3.7 \cdot 10^{13}$
		$Nu_u = 0.9\ Ra'^{0.2}$	$10^{14} \leq Ra' \leq 10^{17}$
	Down	$Nu_d = 0.048\ Ra'^{0.27}$	$10^{12} \leq Ra' \leq 3 \cdot 10^{13}$
		$Nu_u = 0.345\ Ra'^{0.233}$	$10^{14} \leq Ra' \leq 2 \cdot 10^{16}$ $3 \cdot 10^{13} \leq Ra' = 7 \cdot 10^{14}$
	Horizontal	$Nu_h = 0.6\ Ra'^{0.19}$	$10^{7} \leq Ra' \leq 10^{10}$ $5 \cdot 10^{12} \leq Ra' =$
		$Nu_h = 0.85\ Ra'^{0.19}$	10^{14}
Without Internal Heat Generation (Metal Layer)	Up	$Nu_u = 0.0923\ Ra^{0.302}$	$2 \cdot 10^{4} \leq Ra = 2 \cdot 10^{7}$
	Horizontal	$Nu_h = 0.5\ (0.6\ Ra^{0.19} + 0.0923\ Ra^{0.302})$	

It can be noticed in Table 1 that experimentally verified correlations do not exist for every value of Rayleigh number in the range 104 - 1017. Therefore, in the Rayleigh number range for which Nusselt number is not known, a reasonable extrapolation of nearest available correlation has to be made. For natural convection heat transfer in the horizontal direction in the metal layer, no well-tested correlation is available. Therefore, an average of two correlations is being suggested. The surface area of the

vertical walls in contact with the metal layer is small relative to the surface area for heat transfer in the vertical direction, it is expected that even an approximate value of Nusselt number in the horizontal direction would not introduce any significant error.

4. IMPLEMENTATION OF STRATIFIED HEAT TRANSFER MODEL INTO COUPLE MODEL

The COUPLE model in SCDAP/RELAP5 calculates the transient temperature distribution in the lower head of a reactor vessel and in the solid and molten debris supported by the lower head. The user has the option of choosing either a homogeneous or a stratified molten pool. If the pool containing partial or completely molten core material is homogeneous, COUPLE, will calculate heat transfer in the region in an existing algorithm. The only change will be that some Nusselt number correlations may have to be modified. If the user chooses to have two stratified pools, it is proposed that full use of existing model COUPLE be made. The model, COUPLE, uses the effective thermal conductivity concept of each computational cell to calculate the heat transfer behavior. It is proposed that in the modified computational scheme, the new natural convection heat transfer coefficient to calculate effective thermal conductivity be obtained from the correlations given in Table 1. The remainder of the calculation scheme would remain the same. Present numerical scheme to calculate conduction heat transfer and the growth of frozen corium or metal crust would also be retained.

In COUPLE, the transient temperature distribution is calculated by applying heat conduction equations for the lower head and for the regions with solidified or liquefied debris, and by applying correlations for natural convection heat transfer at the liquid-solid interface. The liquid-solid interface include the following locations; (1) molten corium pool facing sides of solidifed crust at the inner surface of the lower head, and (2) molten corium pool facing side of solidified material on top of corium pool.

Subroutine KPOOL in the COUPLE model will be generalized to account for heat transfer at the liquid-solid interface for a stratified molten pool. This subroutine calculates the heat flux due to natural convection on the molten pool side of liquid-solid interfaces. Currently, the subroutine calculates the heat flux only for liquid-solid interfaces for a homogeneous molten pool. The subroutine will be generalized to calculate the heat flux for stratified molten pools. For this case, the natural convection heat flux will be calculated for the following cases; (1) liquid-solid interface along inner surface of lower head and interfacing with molten ceramic material (UO_2 and ZrO_2), (2) liquid-solid interface at top of molten

ceramic material, (3) liquid-solid interface at inner surface of lower head and interfacing with molten metallic material, (4) liquid-solid interface at bottom of molten metallic layer, and (5) top surface of metallic layer.

Subroutine TGPSET in the COUPLE model will be generalized to calculate the average temperature of both molten ceramic and metallic regions. The average temperature of each molten region is applied to calculate the temperature differential term in the equation for heat flux at the molten pool side of the liquid-solid interface. Currently, the subroutine calculates only the average temperature of a well-mixed pool of molten corium. The average temperature is calculated by averaging the temperature of each contiguous finite element with molten material of identical composition. Molten material is represented as being well-mixed by applying a large multiplication factor to the conductivity of stationary molten material.

5. ASSESSMENT OF THE MODEL

In the literature, there are no data available for natural convection heat transfer for a corium pool with stratified metal pool above it. Even a simulated (water and/or Freon) stratified pools (one pool above another one) data are not available. The only available data available are for simulated hemispherical pool and a cylindrical pool simulating the molten metal pool. Moreover none of these pools are with a solidifying boundary. Therefore, in the absence of the desired data and noting that most of the selected correlations in Table 1 are based on the simulated experimental data, only some simple thought problems can be performed. One most important test will be to test if the energy is conserved in the corium and metal pools. Simple integrated energy balance equations can be written for the lower corium pool. Heat transferred to the upper metal pool must be equal to the heat generated in the lower corium pool (decay heat plus latent heat of fusion) minus heat loss and increase in sensible heat, if any. Other test problems can be generated based on the homogeneous numerical analysis of the lower pool by Kelkar et al.[2], Schmidt et al.[3], and O'Brien and Hawkes[15]. However, one has to select the problems that can be simulated by the SCDAP code. The numerical modeling mainly calculates temperature profile and heat flux in the hemispherical pool.

6. CONCLUSIONS

This report provides a simple model for incorporating formation of stratified pools in the lower head. An internal heat generating corium pool can form below a molten metal pool. Different natural convection heat transfer correlations were obtained for pools with and without

internal heat generation. It was decided to make use of the existing COUPLE model and its algorithm to reduce the coding cost. Therefore, conduction heat transfer and solidification will be modeled with existing algorithms in COUPLE. Because no exact experimental data are available for stratified corium and molten metal pools, energy conservation and some simple problems will be used to test the model.

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